Chapter 6
Settlement Surveys--Precise Differential Leveling Observations

6-1. Scope

This section covers standards and specifications for performing precise differential leveling surveys, as required to monitor settlements in concrete and embankment structures. The standards described are developed around precision leveling instruments used for long-distance geodetic leveling runs. For many structures where level runs are relatively short, adequate results may be obtained with traditional leveling methods (e.g., three-wire or even single-wire observations).

Figure 6-1. Precise leveling runs on levee in Everglades and gate structure. Parallel plate micrometer level with invar rods. (Jacksonville District)

6-2. Precise Geodetic Leveling

Vertical settlement determined by precision differential leveling is performed using compensatory auto-collimation leveling instruments with fixed or attached parallel plate micrometers, and observing invar double (offset) scale metric rods with supporting struts (Figure 6-1). Automated digital bar-code levels may also be used. In general, 1 to 3 fixed reference points (bedrock benchmarks) are used to check for potential movement of various points on the structure. One of the reference points is held fixed with all subsequent vertical changes tabulated relative to this fixed reference point. Vertical ties between reference bedrock benchmarks are performed only to monitor potential movement on the reference points, and to enable selection of the best reference point to hold fixed when two or more benchmarks (BM) are available. Leveling should be referenced to stable benchmarks placed in close proximity to the structure to minimize systematic errors that can accumulate during the transfer of elevation from vertical control outside the project area. A stability monitoring program designed specifically for the network of benchmarks should be established by leveling through each project benchmark. Deep bench, rod extensometers (preferably at least two), placed directly on the structure and anchored at depth in bedrock (isolated from surrounding soil), will also provide a stable vertical reference. If benchmarks are located within the zone of deformation, the vertical network should be made to close on the same benchmark it started from so that relative height differences and closures will provide a measure of internal precision.

a. Leveling standards. Precision leveling shall be performed in conformance with the methods and accuracy specifications contained in NOAA Manual NOS NGS 3, Geodetic Leveling, unless modified in the following guidance. Those performing PICES survey work are expected to be thoroughly familiar with the contents of this reference manual. Other applicable reference manuals include:

- ER 1110-2-1806, Earthquake Design and Analysis for Corps of Engineer Dams
- EM 1110-2-1911, Construction Control for Earth and Rock-Fill Dams
- EM 1110-2-2300, Earth and Rockfill Dams, General Design and Construction Considerations
- EM 1110-1-1904, Settlement Analysis

This last reference provides guidelines for calculations of vertical displacements and settlement of soil under shallow foundations supporting various types of structures and under embankments.

b. Equipment specifications. Specifications applicable to differential leveling equipment for deformation monitoring surveys are presented as follows.

(1) Instruments. Instrumentation used should meet requirements for First-Order geodetic leveling, employing either spirit levels or compensator levels with micrometers, or bar code digital levels. For spirit leveling, the instrument will be an automatic level with telescope magnification of 40 times or better, a compensator with a sensitivity of 10 " per 2 mm level vial graduation, and a parallel plate micrometer capable of 0.1 mm readings.

(2) Leveling staves. The rod to be used should be an invar, double scale rod, or one with a permanently attached circular level, both having graduations equal to the range of the parallel plate micrometer (Figure 6-2).

(3) Turning plates (pins). Turning plates should not be used on turf; driven turning pins will be required in this type of terrain. Turning plates should only be used on pavement or hard packed soil.

c. Instrument calibration requirements. Prior to conducting leveling operations the following calibrations will be performed.

(1) Maintenance. Precise level rods and instruments will be cleaned and lab calibrated-maintained at least annually.

(2) C-factor collimation calibration. The C-factor shall be determined at the beginning of each PICES structure observation in accordance with the procedures outlined in Section 3 of NOAA Manual NOS NGS 3. The C-factor determination is made using Kukkamaki's method, also referred to as a Peg Test (Figure 6-3). A slightly different calibration format used by the Jacksonville District is shown in Figure 6-6 at the end of this chapter.

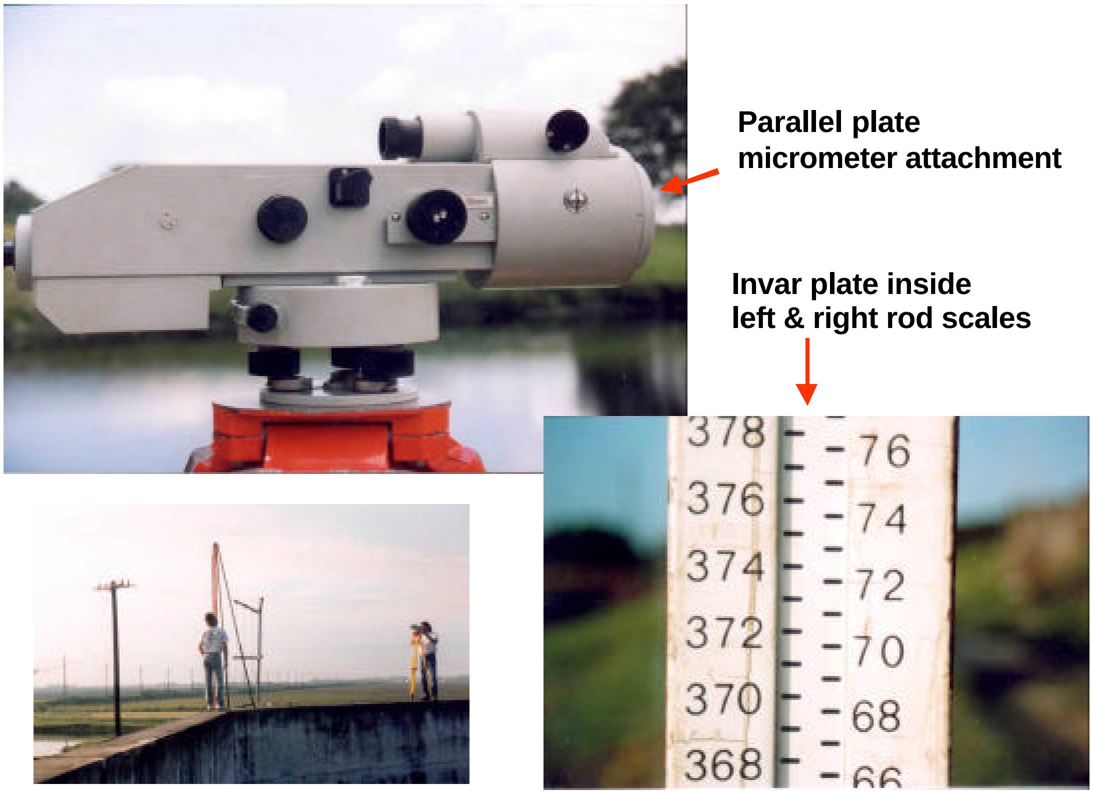

Figure 6-2. Zeiss Ni1 automatic level with parallel plate micrometer attached. Double-scale Invar rod with constant 3.01550 meter difference in left and right scales

(3) Rejection criteria. The C-factor shall conform to the reject/readjustment criteria of Table 3-1 of NOAA Manual NOS NGS 3, which is 0.005 cm/m. Daily C-factor calibrations are not essential provided if the instrument is consistently falling within 0.004 cm/m and backsight/foresight distances (individual setup and accumulated) stay within 1m/2m respectively. C-factor calibrations shall be performed at least twice weekly when continuously leveling at a single PICES structure, upon commencing leveling at a new structure, or daily if the C-factors exceed prescribed limits.

d. Leveling procedures. When determining elevation by precise spirit leveling, the following guidelines will be followed.

(1) Double-run level sections. Sections shall not exceed one kilometer in length. Level lines will be run in two directions. Either one or two double scale invar rods will be used. For short runs, traditional three-wire procedures are allowable. Section runs will be conducted via shortest route between benchmarks.

(2) Sighting convention. Each section shall start and end with the head rod (Rod A) on the BM or reference point. The head rod (Rod A) is always observed first on each setup, whether it is a backsight or foresight observation. The instrument shall be leveled with the telescope pointing towards the head rod (Rod A), thus alternating towards the backsight and foresight at alternate instrument stations.

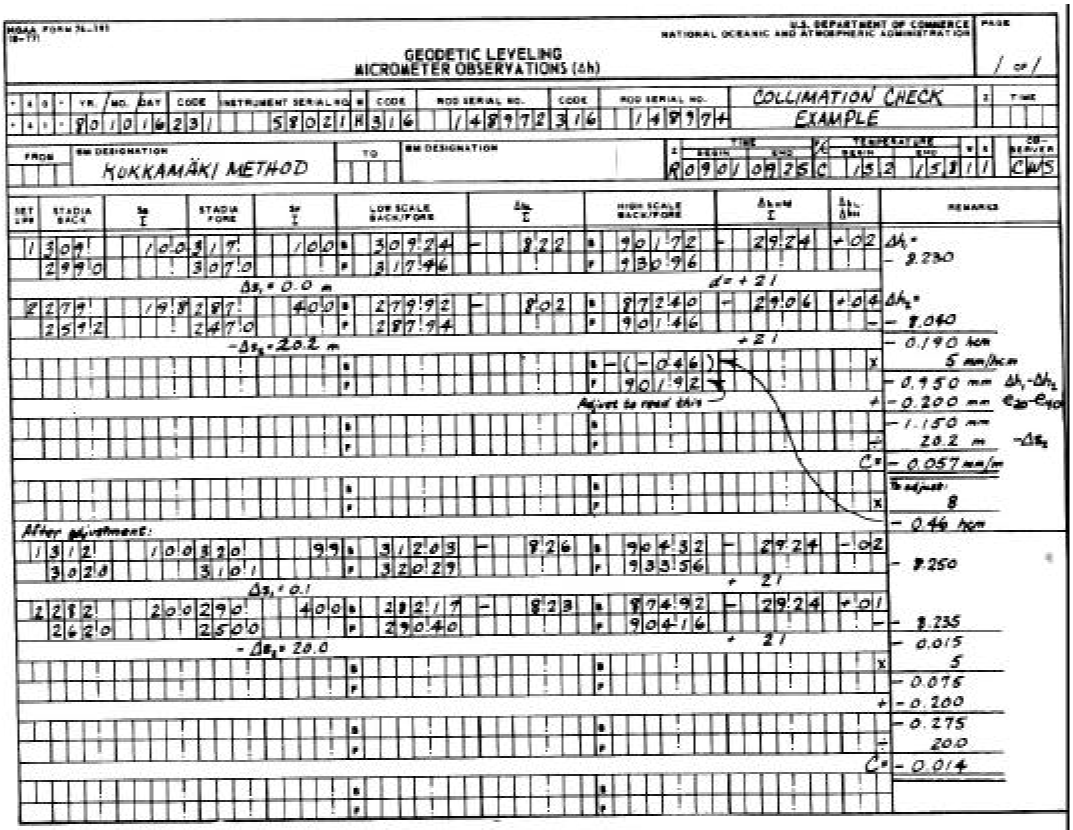

Figure 6-3. C-factor determination using Kukkamaki method

(3) Rod readings. Observing and recording are similar to conventional leveling procedures. The readings will be recorded manually in the field book or electronically to 0.01 mm. An acceptable version of the NGS Micrometer Leveling form may be used (8.5 x 11 inch loose leaf format--Figure 6-4). Field books and data recorders are also acceptable. Level sketches and abstracts shall also be prepared.

(4) Stadia distance. The maximum length of the line of sight should not be more than 50 m. Foresight and backsight distances should be balanced. If the distances cannot be balanced, they will be recorded so that the height difference can be adjusted during data reduction.

(5) Foresight sideshots. Sideshots shall start from a rigid BM and not from a TBM. Multiple foresight shots are allowable from a single backsight assuming distances are allowable.

(6) Rod settlement. If using one level rod, it will be moved from backsight to foresight as quickly as possible to minimize the effects of rod and instrument settlement.

(7) Rod index error. An even number of setups will be made for all differential level section runs in order to eliminate possible rod index errors.

(8) Ground refraction. The line of sight will not be less than 0.5 m above the ground to minimize line-of-sight refraction due to higher temperature gradients near ground level.

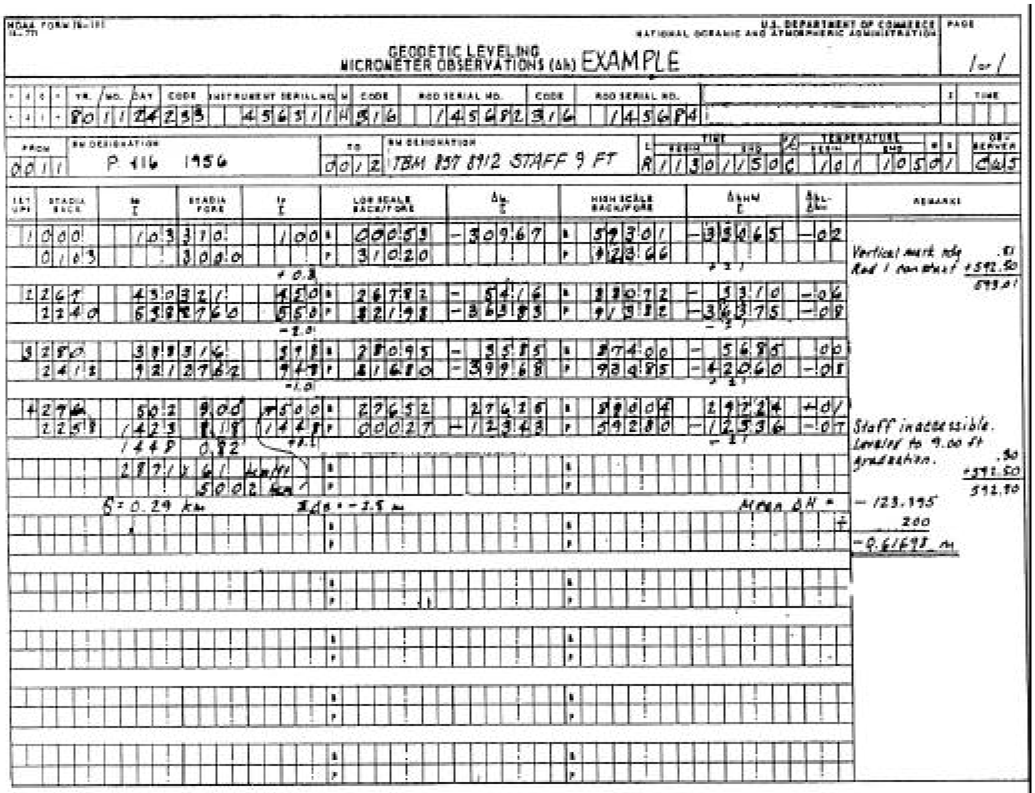

Figure 6-4. Sample precise level notes--parallel plate micrometer leveling with invar rods.

6-3. Differential Leveling Reductions

a. Field checks. Leveling data sheets will be checked in the field with the resulting differential elevation for each run clearly noted, along with pertinent plug offset characteristics, if any, and accumulated stadia lengths per circuit/section. See the example at Figure 6-4. A slightly different recording format developed by Jacksonville District is shown in Figure 6-7 at the end of this chapter.

b. Leveling tolerances. Measurement and closure checks will be made on site with the following tolerances. For additional information on leveling reductions consult NOAA Manual NOS NGS 3.

(1) Single observation. The setup will be re-observed if the disagreement between the left and right side scale elevations on either rod exceeds 0.25 millimeters for that setup.

(2) Stadia distance. Backward and forward stadia distances can differ by no more than 2 meters per setup and 4 meters accumulated along a section.

(3) Re-observation criteria. Re-run level line if external misclosure exceed tolerance value, for newly established points, or for re-observations when misclosures are rejected on single runs.

(4) Closure requirements. Section level run closure tolerances are calculated as follows.

(a) Misclosure tolerance (TOL) for a section run is not to exceed:

$$TOL = \pm 3 \text{ mm} \cdot \text{sqrt}(K) \qquad \text{(Eq 6-1)}$$

where K is measured in kilometers (km)

(b) For short lines, the minimum tolerance for a section run is not to exceed:

$$TOL = \pm 1 \text{ mm (for K less than 0.33 km)}$$

(5) Height difference. If data collected with an automatic level is not rejected, a single height difference shall be computed as the mean of the height difference computed from the left scale readings and the height difference computed from the right scale readings. If the foresight and backsight readings are unbalanced, the single height difference shall be corrected for vertical collimation error.

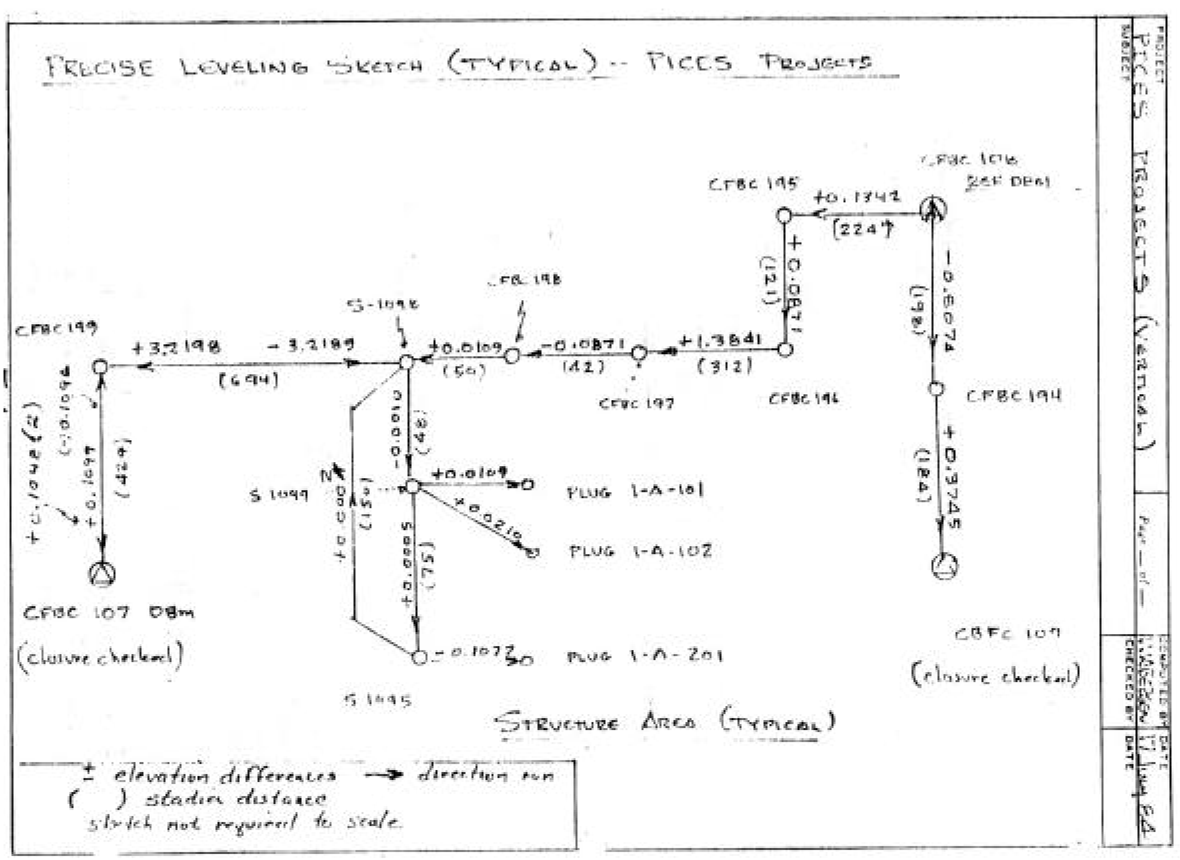

Figure 6-5. Sample sketch of level loops and level lines around a lock & dam structure on Cross Florida Barge Canal (Jacksonville District)

(6) Tabulation accuracy. Record elevations to the nearest ten-thousandth (0.0001) meter on the final reported elevations and settlement. Elevations (and elevation differences) on field sketches and abstracts should be tabulated to the nearest 0.0001 meters.

c. Final height difference reductions. Redundant elevations (i.e., computed from different level loops on circuits from the reference BMs) may be simply averaged regardless of lengths run. Since most leveling surveys will involve lines run directly from a reference BM, final adjusted structure elevations are simply algebraic sums of height differences from the BM using field verified sketch/abstract data.

d. Additional processing. More extensive leveling adjustment procedures, such as least squares processing, may be necessary in the case of:

- Complicated section loop connections,
- Three dimensional adjusted networks,
- Newly established projects,
- Settlement anomalies,
- Abnormal movement of BMs,
- Redefinition of BM elevation using past data.

e. Report tabulation. Tabulated (carried forward) elevations or averaged elevations will be made from the field sketch/abstract, holding the BM elevation fixed and computing changes in elevation from prior observations. Anomalies should be noted on the report tabulation. Recommendations to change the reference BM (to another BM) should be noted and pursued accordingly.

f. Sketches. Field sketches (see sample at Figure 6-5) of level circuits, section, loops, or spurs shall be made to clearly show observed elevation differences, leveling direction, and stadia distances--all taken directly from the (checked) Micrometer Leveling recording forms. From such a sketch, elevations may be easily carried forward from the reference BM -- an essential computation in verifying external misclosures and should be stapled to all the data sheets acquired for an individual structure. Elevations carried forward (from the BM) may be listed on a separate sheet--i.e., an Abstract.

6-4. Total Station Trigonometric Heights

EDM/Total Station trigonometric heighting can be used to determine height differences in lieu of spirit leveling. In general, these elevation differences will not be as accurate as those obtained from spirit/differential levels. Exceptions would occur in mountainous terrain where differential leveling is difficult to conduct. EDM trigonometric height observations conducted over terrain where atmospheric extremes may be present (e.g., across a large valley or river) must be observed using the technique of simultaneous reciprocal measurements.

a. Weather conditions. Observations with an EDM should be limited to days when favorable atmospheric conditions (e.g., slightly cloudy with a light breeze) are prevalent.

b. Setup requirements. Proper targets and instrument height (HI) measuring instruments, as well as sound HI measurement procedures, should be followed at all times.

c. Measurements. Zenith angles and slope distances should be measured in both the direct and inverted telescope positions. Recording and reductions follow similar procedures for horizontal angle and EDM distance measurements.

6-5. Mandatory Requirements

The precise leveling closure and calibration standards in paragraphs 6-3 and 6-4 are considered mandatory.

*	Y R	M O	DAY	CODE	INSTRUMENT SERIAL NO.	M	CODE	ROD SERIAL NO.	CODE	ROD SERIAL NO.		TIME
*											SITE:	

COLLIMATION CHECK - KUKKAMAKI'S METHOD

TIME		F	TEMPERATURE			
BEGIN	END	C	BEGIN	END		OBS

BACKSIGHT					FORESIGHT				
	LOW SCALE					LOW SCALE			
STADIA		HIGH SCALE	SB	(H - L)	STADIA		HIGH SCALE	SF	(H - L)
	$LB	$HB	$	$		$LF	$HF	$	$
	3 0 1 5 5 0					3 0 1 5 5 0			

MEAN BS_1 = __________ **MEAN FS_1** = __________

$BS_1 - FS_1 = h_1$ = __________

	3 0 1 5 5 0		3 0 1 5 5 0

MEAN BS = __________ MEAN FS = __________

e^{20} - .0 0 2 7 e^{40} - .0 1 0 8

BS^2 __________ FS^2 = __________

$BS_2 - FS_2 = h_2$ = __________

$C = \frac{h_1 - h_2}{SF_2 - SB_2}$ = __________ If $C \leq \pm 0.005$ CM/M no adjustment is required

Adjustment : The new correct reading for the high scale foresight rod reading is computed by

New high scale = old high scale - (C X 40) = __________

Figure 6-6. Recording form for Kukkamaki Method of collimation calibration (Jacksonville District)

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LEVELING

STATION NUMBER	THREAD READING BACKSIGHT	ROD READING																STADIA	READING CHECK	ROD AND TEMP
		RIGHT								LEFT										

Figure 6-7. Micrometer leveling observations recording form--left side (Jacksonville District)

FROM BM	TO BM

WIND/SUN	TIME	DATE

THREAD READING FORESIGHT	ROD READING																STADIA	READING CHECK	REMARKS
	RIGHT								LEFT										

Figure 6-7 (continued). Micrometer leveling observations recording form--right side (Jacksonville District)